Implementing Conservation Agriculture Concepts for Irrigated Wheat Based Systems in Northwest Mexico: A Dynamic Process Towards Sustainable Production

Bram Govaerts[1*], Nele Verhulst[1,2], Ken D. Sayre[1], Fabian Kienle[3], Dagoberto Flores[1] and Agustin Limon-Ortega[4]

[1]International Maize and Wheat Improvement Centre (CIMMYT), Mexico, D.F., Mexico

[2]Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven, Celestijnenlaan 200 E, 3001 Leuven, Belgium

[3]Colegio de Postgraduados, Km 36.5 Carr. México -Texcoco, CP 56230, Montecillo, Mexico

[4]INIFAP-CEVAMEX, AP10, Km 17.5 Carr. México-Lechería, CP 56230, Chapingo, Mexico

**Corresponding author (Email: b.govaerts@cgiar.org)*

In this paper we use the example of the irrigated wheat based systems of North Mexico as a typical example of a step-by-step process to advance the use of Conservation Agriculture based Resource Conserving Technologies towards the final goal of the implementation of Conservation Agriculture. Sonora in northwest Mexico. This region is characterized by a desert climate, mostly sunny and dry with a total rainfall of about 381 mm per year with 253 mm during the summer cycle (May – Oct). The Yaqui Valley is one of the main agricultural production areas encompassing nearly 255,000 ha of irrigated land using primarily gravity irrigation systems fed by canals (over 80% of irrigation water) and deep tube wells (around 20% of irrigation water). Crops planted during the winter cycle are wheat (November-May), safflower (January-June), winter maize (September-February), chickpea (December – April) while during the summer cycle summer maize (May – October), sorghum (March – July), dry beans (March – May) are most common. There have been 3 main shifts in farming system practices during the last decades: (1) In 1981, the majority of the farmers were planting with ‘melgas’ (crops planted in solid stands on the flat with flood irrigation in basins) with only 6% of farmers in the valley planting on raised beds. However by 1996, 90% of the farmers had shifted to planting on raised beds. The great benefits from bed planting are reduced production costs, reduced irrigation water use, enhanced field access which facilitates control of weeds and other pests, and timely and efficient application of nutrients, reduced tillage, and crop residue management. (2) Another remarkable change in farmer practices has been crop residue management. In the 1992/93 cycle, residues were burned by 95% of the farmers. This practice was deeply entrenched. By 2001, however, 96% of the farmers are no longer burning but incorporating the residue. (3) Recently there is growing interest to take the next logical step in making raised bed planting more sustainable by reducing tillage and manage crop residues on the surface by reusing permanent raised beds with only superficial reshaping in the furrows between the raised beds as needed before planting of each succeeding crop, following even distribution of the previous crop residues. Therefore in 1991 the crop management team at CIMMYT started research on permanent beds to offer farmers opportunities to further reduce production cost andincrease sustainability of the system through the positive effects on chemical, physical and biological soil quality.

Keywords: permanent raised bed planting, residue management, irrigated wheat systems, resource conserving technologies

In many parts of world, agricultural practices are determinant in food production. Adoption of new agricultural technologies, intensification of agriculture and improved crop varieties have dramatically increased crop yields in developing countries (Gupta and Seth, 2007). However, modern society demands cropping systems that not only aim at stable and high yields, but also maintain soil fertility, reduce negative effects for the environment and are economically sound (Lal, 1997).

Farmers concerned about the environmental sustainability of their crop production systems combined with ever-increasing production costs have begun to adopt and adapt improved management practices for their cropping systems that lead towards the ultimate vision of sustainable conservation agriculture solutions. Conservation Agriculture combines the following basic principles:

1. **Reduction in tillage**: The objective is the application of zero tillage or controlled tillage seeding systems that normally do not disturb more than 20-25% of the soil surface
2. **Retention of adequate levels of crop residues and surface cover of the soil surface**: The objective is to maintain an adequate soil cover through the retention of sufficient crop/cover crop residues on the soil surface to protect the soil from water/wind erosion, water run-off and evaporation to improve water productivity and to enhance soil physical, chemical and biological properties associated with long term sustainable productivity;

3. **Use of crop rotations**: The objective is to employ economically viable, diversified crop rotations to help moderate/mitigate possible weed, disease and pest problems and offer economically sound cropping alternatives to help minimize farmer risk.

These conservation agriculture principles seem to be applicable to a wide range of crop production systems including low-yielding, dry rain-fed as well as high-yielding irrigated conditions. However, how these principles are applied will depend on the situation and will need a flexible approach as a function of different production systems. Obviously, specific and compatible management components (weed control tactics, nutrient management strategies and appropriately-scaled implements.) will need to be identified through adaptive research with active farmer involvement to facilitate farmer adoption of appropriate CA-based technologies for contrasting agro-climatic/production systems. As such, the movement towards CA-based technologies normally is comprised of a sequence of stepwise changes in cropping system management to improve productivity and sustainability. The principles of marked tillage reductions are initially applied in combination with the retention of sufficient amounts of crop residue on the soil surface, with the assumption that appropriate crop rotations can be included or maintained to achieve an integrated, sustainable production system. Local soil and environmental conditions will determine if zero-tillage, strip tillage, permanent raised bed planting, or any other reduced tillage system is the best alternative. Local market conditions, crop production level, farming system and environment will determine the residue management strategies but with the near certainty that unless adequate residues are not retained, marked reductions in tillage will unlikely be feasible over the long term. In this paper we use the example of the irrigated wheat based systems of North Mexico as a typical case of a step-by-step process that involves the application of CA-based Resource Conserving Technologies towards the final goal of the implementation of Conservation Agriculture.

The Yaqui Valley in Sonora, Mexico

Sonora, located in the northwest of Mexico, is characterized by a desert climate, mostly sunny and dry with total amount of rainfall is about 381 mm per year with 253 mm from June to August during extreme rain events in the summer cycle (1971-2000). Average day-time temperatures during the grain filling stage are moderate (18ºC) for wheat and hot (31ºC) for summer maize. Sonora has national and international importance for wheat production, especially the Yaqui Valley which forms a part of the North-West Mexican coastal plains and is located 27.33 N, 109.09 W and 38 masl (Figure 1). The valley represents a microcosm of events characterizing the progress in wheat production that has occurred around the world over the past 40 years. This valley was the center of the wheat improvement program that Dr. Norman Borlaug and his colleagues initiated in Mexico in the mid 1940s. From this modest program came the remarkable semi-dwarf wheat germplasm that dramatically increased wheat yields in Mexico, especially in irrigated areas. This material also constituted the initial introductions sent to South Asia (especially India and Pakistan) that stimulated the Green Revolution in wheat production during the mid to late 1960s. Much of the initial seed of the new, semidwarf varieties in south Asia was produced and exported by farmers in the Yaqui Valley (Sayre and Moreno-Ramos, 1997).

This valley encompasses about 255,000 ha of irrigated land using primarily gravity irrigation systems fed by canals (over 80% of irrigation water) and deep tube wells (around 20% of irrigation water). Farming is mechanized but operational farm size can range from less than 10 ha to several hundred hectares or more. Crops planted during the winter cycle are wheat (November-May), safflower (January-June), winter maize (September-February) and chickpea (December – April) while during the summer cycle summer maize (May – October), sorghum (March – July) and dry beans (March – May) are most common. (Aquino, 1998).

Four planting methods are traditionally practiced by wheat farmers in the Yaqui Valley (Aquino, 1998):

1. *Melgas*. This is the traditional system of planting wheat on flat seedbeds. Wheat seed is either broadcast and incorporated (generally with a harrow), or seeded with a small grain drill in rows spaced from 15 to 25 cm. Borders are raised to form the *melgas* (basins), the size and shape of which depend on how well the field has been levelled. The farmer can subdivide the field into straight *melgas* on levelled fields or into *melgas* that follow the contour of the land (*curvas de nivel*) (Figure 2).

2. *Corrugations.* Wheat is seeded as for *melgas*, either broadcast or with a small grain seeder. However, instead of raising borders, farmers make a shallow furrows spaced 70 to 90 cm apart to carry irrigation water.

3. *Planting on beds*. The use of a raised seed bed (60 - 90 cm) with two - four rows on the bed for wheat, one for maize and one or two for sorghum.

Figure 1. Location of the Yaqui Valley, Sonora in Mexico

Figure 2. Traditional planting in the Yaqui Valley of Sonora in melgas

4. *Permanent raised beds:* The use of raised bed planting systems, reshaping the original beds with only superficial soil movement in the furrows between the raised beds as needed before planting of each succeeding crop with no tillage on the surface of the beds, ideally combined with even distribution of the previous crop residues on the soil surface.

Figure 3. Conventionally tilled raised beds planted with wheat (left) and maize (right)

Conventionally Tilled and Permanent Raised Beds

Briefly, this technology consists of seeding 1-4 rows depending on the crop on the raised beds, 70-90 cm wide. Bed height is normally 15-30 cm. Irrigation water is applied to the corrugations between the beds. The system facilitates a pre-seeding irrigation to eliminate the first generation of weeds by doing shallow tillage at the time of seeding into the residual moisture. Currently most farmers use conventional tillage prior to making the beds for wheat planting; incorporating the residues of the previous crop. The system allows mechanical cultivation as an alternative method of weed control during the crop cycle including small grain crops like wheat and barley. It also makes hand weeding an economical option because of the easy field access resulting from row orientation on the beds. Irrigation water management is more efficient and less labor intensive with the use of furrows, compared to the traditional flood irrigation system.

Moreno et al. (1982) provide a brief summary of the research conducted in the Yaqui Valley to establish the basis for the raised bed planting system used on irrigated wheat in Mexico. In the early 1960s, research on the effect of different row spacing on wheat were initiated. The results showed similar yields for a wide range of spacing (from 17 to 70 cm) and demonstrated the feasibility of modifying how wheat can be planted with reduced seed rates by implementing raised bed systems. In the late 1970s a concerted effort was made to introduce and transfer this technology to farmers and the effort was successful. In 1981, only 6% of farmers in the valley were planting on beds; while by 1996 over 90% of farmers were using the system. This adoption has been paralleled by similar increases in the use of pre-seeding irrigation as an efficient part of weed control (which also ensures better stand establishment for the common heavy clay soils) and in the use of mechanical cultivation during the crop cycle for weed control (Sayre and Moreno–Ramos, 1997).

Another remarkable change in farmer practices has been the way crop residues are managed. In the 1992/93 cycle, residues from the wheat harvest were burned by 95% of the farmers and the practice was deeply entrenched. When asked how they would manage the residues from the 1993/94 cycle, 94% of farmers answered that they would continue burning it. Most respondents (75%) stated that they burn residues because of the short time available to prepare land and establish the crop for the spring-summer cycle (Aquino, 1998). In 2001, however, 96% of the farmers were no longer burning but were incorporating the residue. This is a clear example of a first step in the continuum towards sustainable systems. Conventional raised beds, however do not meet the criteria of CA but can be considered as a CA-based Resource Conserving Technology that prepares the terrain for further development to more sustainable systems.

The next step for these irrigated systems to increase sustainability was to apply the CA concepts to reduce tillage and manage crop residues on the surface by reuse of the existing raised beds with only superficial reshaping in the furrows between the raised beds as needed before planting of each succeeding crop, following even distribution of the previous crop residues (Sayre, 2004) (Figure 4). Permanent raised beds permit the implementation of crop residue strategies to maintain a permanent soil cover for greater rainwater capture and conservation.

Figure 4. Permanent raised beds planted with soybeans in remaining wheat stubble (left) and wheat planted in maize straw (right

The Scientific Base for Permanent Raised Beds

In 1991 CIMMYT and local partners showed interest in the development of permanent raised bed production technologies based on the CA principles. These would have the potential to reduce production costs, improve input-use efficiency, permit more rapid turn-around between crops and provide more sustainable soil management while still allowing the use of the existing, widespread gravity irrigation system. Therefore, a long-term experiment was initiated in 1992 in the Yaqui Valley to compare common farmer practice (based on extensive tillage to destroy the existing raised beds with the formation of new beds for each succeeding crop), with the permanent raised bed system combined with different crop residue management options. Also several component technology trials to fine-tune different aspects of the permanent bed planting system were implemented. A detailed description of the experiments can be found in the different publications referred to below.

Crop Yields and Economic Performance with Different Long-term Bed Planting Practices

As can be observed in Figure 5, there have been large annual changes in wheat yields. Low wheat yields in 1995 and 2004 were the result of extended warm, cloudy periods during the first half of the crop cycles. However, the key outcome seen in Figure 5 is that yield differences between management treatments clearly diverged after 5 years. There were no significant wheat yield differences between any of the tillage/residue management practices for the first 5 years (10 crop cycles). However, yield differences between management treatments clearly diverged with a dramatic overall reduction in the yield for permanent beds where all residues have been routinely burned from onset of the trial, after the initial 5 years. The effect from management practices in irrigated agriculture systems (at least for tropical, semi-tropical and the warmer, temperate areas), appears to be “hidden or postponed” by the irrigation water applied until a level is reached that no longer can sustain yield even with irrigation. Research to characterize tillage and residue management issues must therefore include a time horizon at least five or more years to insure that potential differences between management practices have adequate time to be expressed. Full retention and partial retention of residues had a similar yield expression, indicating that for irrigated systems with the associated high residue yields, substantial amounts of residue probably can be removed for other economic uses without suffering a yield decline (Sayre et al., 2005).

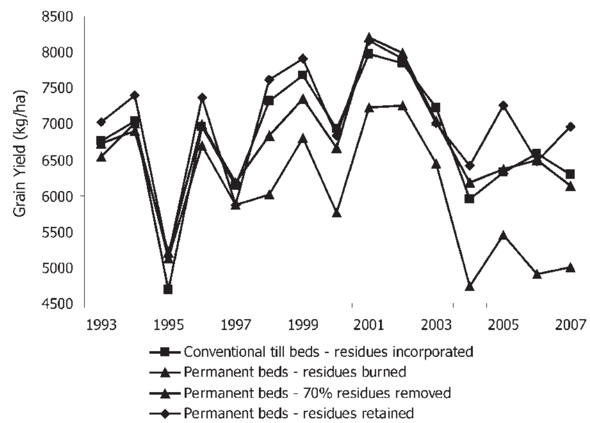


Figure 5. The effect of tillage and residue management on wheat grain yields (kg/ha at 12% H2O), CIMMYT long-term sustainability trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico, 1993-2006 (Adapted from Sayre et al., 2005)

Although the yields of properly managed permanent beds are not markedly higher than conventionally tilled beds with residue incorporation, permanent beds production costs are markedly lower. Figure 6 illustrates the clear yield and economic advantage of permanent raised beds over conventionally tilled beds. These results are derived from a large-scale trial/farmer demonstration module where crops are planted when possible for each planting system (usually 7-10 days earlier for wheat in the permanent beds as compared to tilled beds due to faster turn-around between crops).

Similar economical benefits were observed in the summer sorghum crop planted farmer fields (Figure 7). With the conventional planting system, the minimum production of the crop to recover costs was 4.6 ton/ha while for the permanent raised beds system this point is already reached with 3.4 ton/ha. The increased production and reduced costs with permanent raised beds resulted in a cost-benefit ratio of 1.6 as opposed to 1.2 for conventionally tilled raised beds. For the marked economic advantages of the permanent raised-bed planting systems, farmers in the Yaqui Valley are now in the early stages of adopting the system (Figure 7).

A further step in implementing the CA principles is through taking advantage of the reduced turn around time between crops with reduced tillage systems and including emphasis on augmenting cropping diversity offering farmers alternative, economically viable crop rotation options. Sound crop rotations can result in positive yield

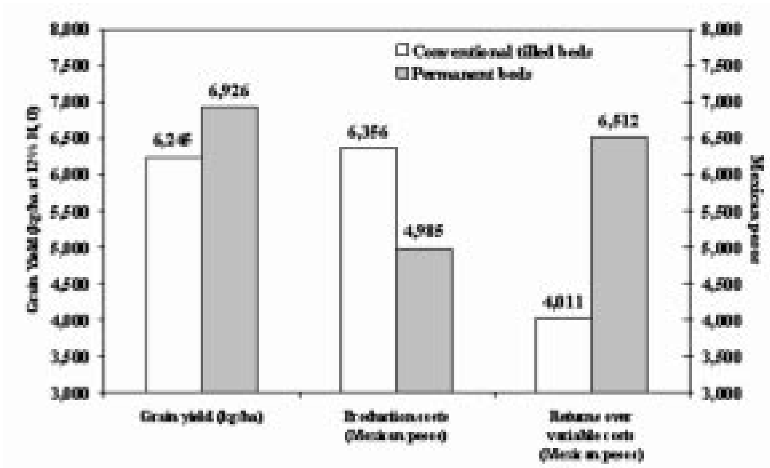


Figure 6. Comparison of average wheat grain yields, variable production costs and returns over variable costs of wheat produced with conventional tilled beds versus permanent raised beds conservation agriculture trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico, 1993-2006

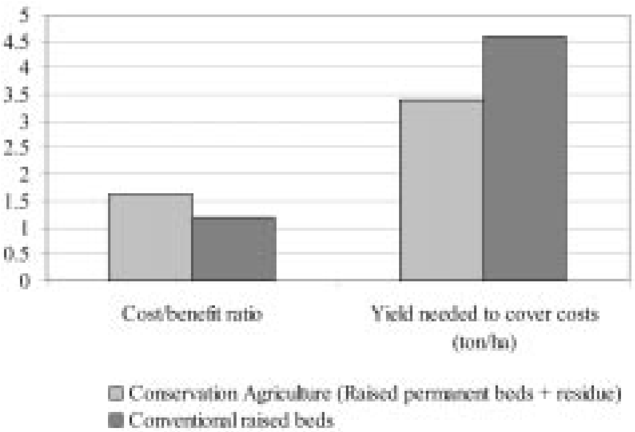
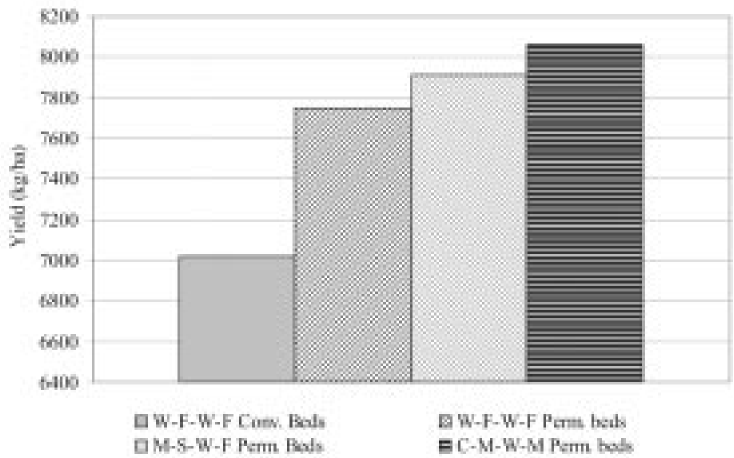


Figure 7. Comparison of cost/benefit ratio and yield required to cover cost for a sorghum summer crop with conventional tilled beds versus permanent raised beds in a farmer field of the Yaqui Valley, Sonora, Mexico

increases for the different crops in a rotation. Figure 8 shows that wheat yields are higher in systems that involve more diverse rotations, as compared to the wheat-fallow system, especially when a legume, in this case chickpeas, is included in the rotation.

Soil Quality and Soil Degradation as Influence by Different Tillage Systems

Several soil related parameters were measured in the long-term raised bed planting trial. A clear increase in stable macroaggregation was observed for permanent raised beds with residue retention compared to conventionally tilled raised beds (Table 1). Burning of residues also had a detrimental effect on soil aggregation although to a lesser extent than tillage. The effect of the decreased aggregate stability is reflected in the soil erosion by irrigation water as well as in the time-to-ponding (a rapid method to determine a soil's potential water infiltration capability). The soil loss for conventionally tilled raised beds was significantly higher compared to permanent raised beds when residues are retained (Figure 9). A longer time-to-ponding indicates that the soil has more potential infiltration ability. The time before ponding occurs is brief and very brief for tilled beds with residue incorporated and for permanent beds with the residues burned, respectively (Figure 10). However, as the level of retained residues increases with the permanent beds, time-to-ponding increases sharply, an indication that water infiltration potential also will dramatically increase. Not only is water infiltration improved, but also the soil moisture conservation in the permanent bed planning system with residue retention is better compared to conventionally tilled beds (Figure 10).



W= Wheat; F= Fallow; S= Sorghum; M= Maize; C= Chickpea; Perm. Beds= Permanent raised beds; Conv. Beds= Conventionally tilled beds

Figure 8. Effect of tillage and crop rotation on wheat grain yield averaged for 2006 and 2007 at CIMMYT long-term sustainability trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico

Table 1. Effect of tillage and crop residue management on soil properties (0-7 cm) for the CIMMYT long-term bed planting trial Sonora, Mexico (Adapted from Sayre et al., 2005; Limon-Ortega et al., 2006).

Tillage/ResidueManagement	% Organic Matter	Na (mg kg_{soil-1})	Aggregate Distribution MWD (mm)	Aggregate Stability MWD (mm)	SMB C (mg kg_{soil-1})	SMB N (mg kg_{soil-1})
Conv. BedsResidue incorporated	1.23	564	1.32	1.262	464	4.88
Permanent BedsBurn Residue	1.32	600	0.97	1.12	465	4.46
Permanent BedsPartial Removal Residue	1.31	474	1.05	1.41	588	6.92
Permanent BedsRetain Residue	1.43	448	1.24	1.96	600	9.06
Mean	1.32	513	1.15	1.434	552	6.40
LSD (P=0.05)	0.15	53	0.22	0.33	133	1.60

MWD= Mean Weight Diameter; SMB N= Soil microbial biomass – C content; SMB N = Soil microbial biomass – N content; Conv. Beds= Conventionally tilled beds

Results of this work also indicate that the long-term use of permanent beds with all crop residues retained increases C and N from the SMB over time (Table 1). The apparent amelioration of Na levels for permanent beds with partial or full residue retention (Table 1) may have great potential for vast areas where soil salinity is an increasing problem associated with gravity-based irrigation systems (Sayre et al., 2005; Limon-Ortega et al., 2006).

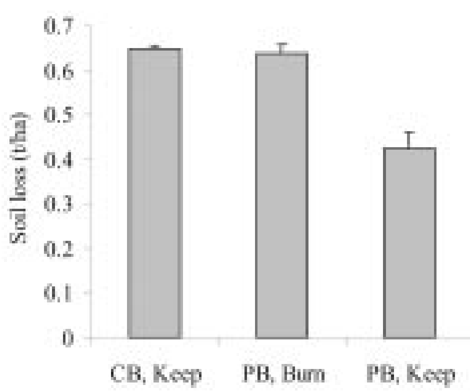


Figure 9. Effect of tillage and crop residue management on soil loss (t/ha) for the CIMMYT long-term sustainability trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico

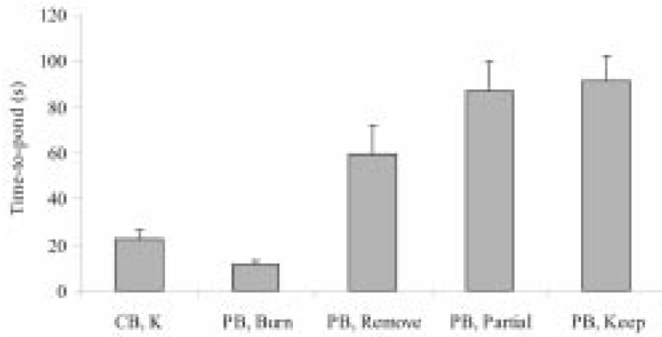


Figure 10. Effect of tillage and crop residue management on time-to-pond for the CIMMYT long-term sustainability trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico

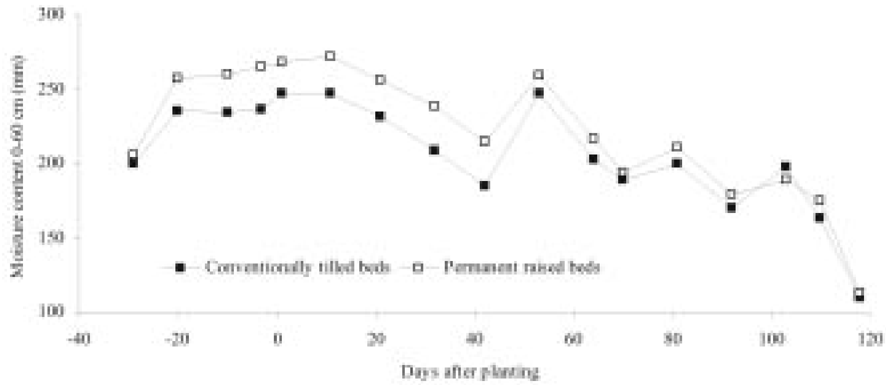


Figure 11. Effect of tillage on soil moisture (mm) through the soil profile (0-60 cm) in the CIMMYT long-term sustainability trial on irrigated wheat systems, Yaqui Valley, Sonora, Mexico

Farmers Applying Permanent Raised Bed Planting in the Yaqui Valley, Sonora, Mexico

Because of the promising results of the above described trials there has been increasing interest by farmers and organizations to adopt the permanent bed technology in the Yaqui Valley of Sonora, Mexico. PIEAES, a local farmer organization, supported actively the development of an on-station farmer training module. The module is now jointly managed by the CIMMYT crop management team and PIEAES and serves as the training platform for recent new initiatives. In 2007 extension projects were started that aim at training farmers, farm managers, technicians, tractor drivers among others, in the permanent raised bed technology. Also in 2007 the Mexican Wheat Chain Organization started a progam that supported the purchase by farmer groups of CA planters.

When moving to permanent raised beds farmers have continued to use a similar sized raised beds (70 to 80 cm from furrow to furrow) in line with the bed widths that have routinely been used by farmers for conventional tilled beds. By maintaining the same bed widths that farmers are already using for tilled beds, it has been easier, whenever feasible, to modify existing implements for use with permanent beds as well as to eliminate the need to alter tractor wheel spacing already in use. The goal has been to attempt to utilize the permanent beds continuously for as long as feasible and possible.

The main factor that has limited extension and adoption of permanent raised beds (and essentially most other relevant CA technologies) in the past has been the utter lack of appropriate implements, especially seeding equipment. In many ways the development of prototype implements for seeding on permanent beds with retained residues, for band application of fertilizers on permanent beds and for maintaining the shape of the beds, has been the most important issue to confront. Therefore, the philosophy the Mexico based CIMMYT crop management team has been to develop multi-crop/multi-use implements that can be simply reconfigured to reshape beds, band apply basal or post-emerge fertilizer and seed both small and large seeded crops easily and rapidly (Figure 12).

The prototype developed has fertilizer and seed tanks with appropriate distribution mechanisms that can seed both small and large seeded crops with an acceptable level of precision using a multiple tool bar arrangement to mount all needed attachments with adjustable clamp systems (fertilizer/seed tanks and their distribution systems, seed openers, fertilizer opens, residue management tools like discs or residue cleaners and shovels or discs for bed reshaping). The goal is to have a single implement capable of being easily and rapidly reconfigured to perform most seeding, fertilizing and bed permanent bed management activities for the crops grown by these farmers to markedly reduce the machinery costs as farmers convert from conventional, flat planting systems to permanent beds.

Figure 12. Left-Multi-crop/multi-use implement configure for reshaping permanent beds and applying basal fertilizer; Right-Same implement configured for bed reshaping, fertilizing and maize planting.

There are now irrigated permanent beds with the farmers using the multi-crop multi-use implement now commercially available in the Yaqui Valley that have supported up to 4 consecutive crops of wheat, maize and safflower but while still in a very initial stage of adoption, the area is growing. It will be of utmost importance that farmers, local organizations and scientists from all disciplines keep working together to support further extension and solve second generation problems where needed.

Conclusions

The system of raised bed planting for irrigated conditions that has been widely adopted by farmers in northwest Mexico and offers an innovative option for diversifying wheat production practices in other, similar areas around the world. Bed planting offers many advantages in irrigated production systems. The great benefit resulting from bed planting is reduced production costs, reduced irrigation water use, and marked, enhanced field access, which facilitates control of weeds and other pests, the timing and placement of nutrients, tillage reductions, and crop residue management.

The next logical step to make raised bed planting more sustainable is to reduce tillage and manage crop residues on the surface by reuse of the existing raised beds with only superficial reshaping in the furrows between the raised beds as needed following even distribution of the previous crop residues before planting each succeeding crop,. Permanent raised beds will further reduce production cost and will increase sustainability of the system through the positive effects on chemical, physical and biological soil quality. Providing farmers with viable management alternatives should be the primary role of agricultural scientists.

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